Development of CAPP/GAMMA+ Code System for Neutronics/Thermo-fluid Coupled Analysis of a Prismatic VHTR Core

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1. Introduction

Computer codes for very high temperature reactor (VHTR) analysis and design are being developed at Korea Atomic Energy Research Institute (KAERI). The DeCART code is developed for high fidelity neutronics analysis and for the generation of cross-sections in two-step neutronics analysis procedure [1]. The CAPP code is a 3-dimensional nodal code for core physics analysis and simulation [2]. The GAMMA+ code is a system/ safety analysis code for thermo-fluid and system transient [3].

Coupled code systems are also being developed for neutronics/thermos-fluid coupled analysis of VHTR. CAPP/GAMMA+ coupled code system is developed for coupled steady state analysis and coupled transient analysis. In this paper, the CAPP/GAMMA+ coupled code system is presented. A server program named INTCA was developed for the coupling of the two codes as well.

2. Coupled Code System

2.1 CAPP Code

The multi-group neutron diffusion equation is solved based on the block nodalization and the finite elements shown in Fig. 1. A block is divided into six triangular prisms radially and each of them is axially divided into several homogeneous zones. A triangular prismatic finite element is assigned for each homogeneous zone. Four types of the triangular prismatic finite elements shown in Fig. 1 can be chosen depending on the order of the element function. Four types of core model can be used : one sixth, one third, half, and full core model. Rotational symmetry condition is imposed on the internal boundary of the core models except for the full core model.

The microscopic cross-sections are represented as a function of burnup, moderator temperature, and fuel temperature as shown in Eq. (1). The first term of the RHS of the Eq. (1), $\sigma_{xg}^{j,ref}$, is the *g*-group *x*-type cross-section of nuclide *j* at the reference temperature state. The second and the third term, $\Delta\sigma_{xg}^{j,T_m}$ and $\Delta\sigma_{xg}^{j,T_f}$, are the increment of the cross-section due to the moderator temperature and fuel temperature variation, respectively.

$$\sigma_{xg}^{j}\left(b,T_m,\sqrt{T_f}\right)=\sigma_{xg}^{j,ref}\left(b\right)+\Delta\sigma_{xg}^{j,T_m}\left(b,T_m\right)+\Delta\sigma_{xg}^{j,T_f}\left(b,\sqrt{T_f}\right), \quad (1)$$

where b, T_m, and T_f represent burnup, moderator temperature, and fuel temperature, respectively.

Micro depletion calculation with the user-defined nuclide chain is performed for each homogeneous zone by using the one-group cross-sections and the one-group flux determined by the neutron flux solver. Fig. 2 shows typical heavy nuclide chain for uranium fuel, fission product chains, and burnable absorber chain for B_4C burnable absorber.

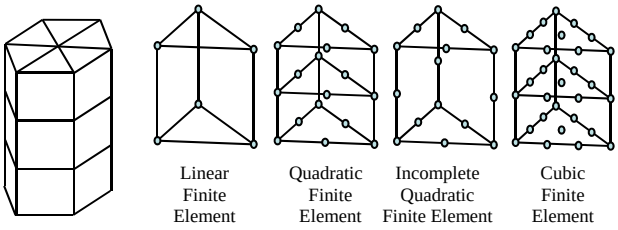
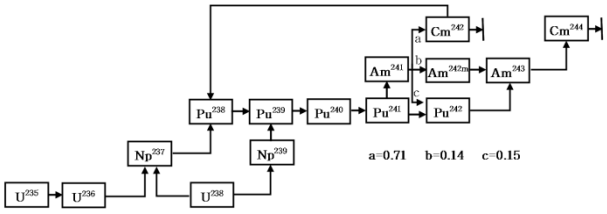
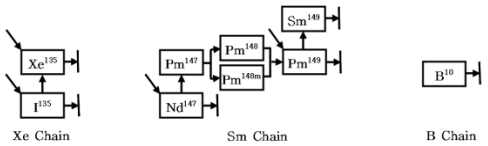


Fig. 1. Block nodalization and the finite elements.



(a) Heavy nuclide chain for uranium fuel



(b) Fission product and burnable absorber chain

Fig. 2. Typical nuclide chain for uranium fuel with B_4C burnable absorber.

2.2 GAMMA+ Code

The GAMMA+ code has the capability of multi-dimensional multi-component mixture analysis to investigate various phenomena of a high temperature gas cooled reactor such as pressurized or depressurized conduction cool down and air/water-ingress accidents.

For fluid, the continuity (or mass conservation) equation, momentum conservation equation, energy conservation equation, and species conservation equation are solved simultaneous. Three different scales

of heat conduction models are used in GAMMA+. These are (1) a heat conduction model in TRISO particles, (2) an implicit heat conduction model between TRISO particles and the fuel compact, and (3) a multi-dimensional heat conduction model with fuel or reflector blocks.

2.3 Code Coupling

Fig. 3 shows the CAPP/GAMMA+ coupling scheme. A server program named INTCA is used to control the coupled calculation of CAPP and GAMMA+. The CAPP code calculates the power density and the fast fluence and sends them to GAMMA+. The power density data are used as heat source in GAMMA+. The fast fluence is used for evaluating the conductivity of graphite material. On the other hand, GAMMA+ calculates core temperatures and sends them to CAPP. The temperature data are used to evaluate nuclear cross-sections in CAPP. The nuclide number densities in Fig. 3 will be used in the accident conditions such as air/water-ingress.

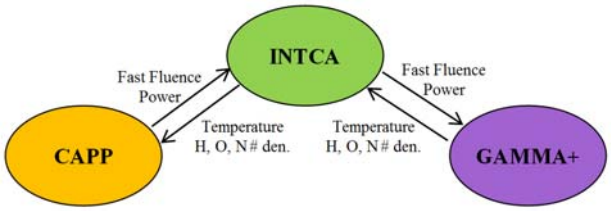
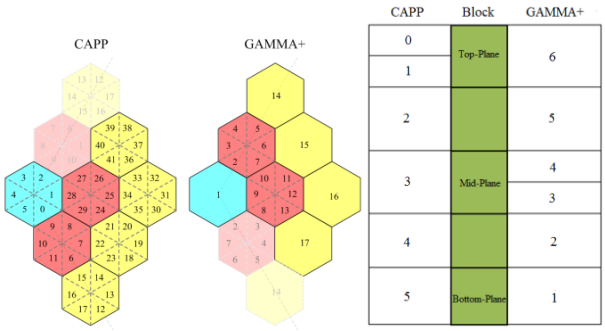


Fig. 3. CAPP/GAMMA+ coupling scheme.

Fig. 4 illustrates an example of the computational cells of the CAPP and GAMMA+ codes. The GAMMA+ code uses either hexagonal or triangular radial cells while the CAPP code uses triangular radial cells. For instance, the six triangular cells of the CAPP code, cells 30~35, correspond to the hexagonal cell 16 of GAMMA+. The average of the power densities of the six triangular cells of CAPP with volume weighting is assigned to the power density of the cell 16 of GAMMA+. And the temperature of the cell 16 of the GAMMA+ code is assigned to the temperatures of the six triangular cells of the CAPP code. The mapping of the axial cells can be done in the same way as in the radial cells. Once the spatial discretization is determined, the mapping matrices for the variable transformation from the CAPP code to GAMMA+ code and the inverse transformation can be determined. The transformation of the variables is done by INTCA as follows :

$$\mathbf{Q}^G = \mathbf{M}_{GC}\,\mathbf{Q}^C \quad \text{and} \quad \mathbf{T}^C = \mathbf{M}_{CG}\,\mathbf{T}^G, \qquad (1)$$

where $\mathbf{M}_{GC}$, $\mathbf{M}_{CG}$, $\mathbf{Q}^C$, $\mathbf{Q}^G$, $\mathbf{T}^C$, and $\mathbf{T}^G$ are the mapping matrix from CAPP to GAMMA+, the mapping matrix from GAMMA+ to CAPP, the power density vector in CAPP, the power density vector in GAMMA+, the temperature vector in CAPP, and the temperature vector in GAMMA+, respectively.



(a) Radial configuration (b) Axial configuration

Fig. 4. Example of the computational cells of CAPP and GAMMA+.

Fig. 5 shows the flowchart of the server, INTCA. After generating the mapping matrices INTCA waits for the connections from the clients. Right after making connections with the clients, INTCA repeatedly (1) receives requests from the two client codes, (2) determines which job to do based on the requests from the clients, (3) sends commands to the clients, and (4) mediates between the two clients for exchange of the coupling data if necessary until one of the requests from the clients is “Stop”.

Fig. 6 shows the flowchart of the CAPP code for coupled depletion calculation with critical control rod position search. The CAPP code repeatedly (1) sends “Solve” request to the server, (2) receives command from the server, (3) updates the power distribution using the latest temperature distribution received from GAMMA+, (4) sends the power distribution, and (5) receives nuclide number densities and temperature distribution until convergence. Once the converged solution is obtained, CAPP checks the criticality of the reactor. If the reactor is not critical, CAPP adjusts the rod positions to make the reactor critical and starts a new coupled calculation. If the criticality of the reactor is achieved, CAPP proceeds with depletion calculation for the next burnup step until the final burnup step. At final burnup step, CAPP sends a request “Stop” to INTCA and closes the connection with INTCA.

Fig. 7 shows the flowchart of the GAMMA+ code for coupled steady state calculation. Unlike the CAPP code, GAMMA+ has only transient calculation mode and the steady state solution is obtained by performing null-transient calculation. The GAMMA+ code makes connection with the INTCA server after reading the input file. The GAMMA+ code repeatedly (1) sends “Solve” request to the server, (2) receives command from the server, (3) updates the temperature distribution using the latest power distribution received from CAPP by simulating the time period t~$t+\delta$ in GAMMA+ problem time, (4) receives the power distribution, and (5) sends nuclide number densities and temperature distribution until convergence. Once the converged solution is obtained, GAMMA+ checks the problem time. If the problem time in GAMMA+ is less than the maximum problem time given by the user, GAMMA+

starts a new coupled calculation. Otherwise, GAMMA+ sends a request "Stop" to INTCA and closes connection with INTCA.

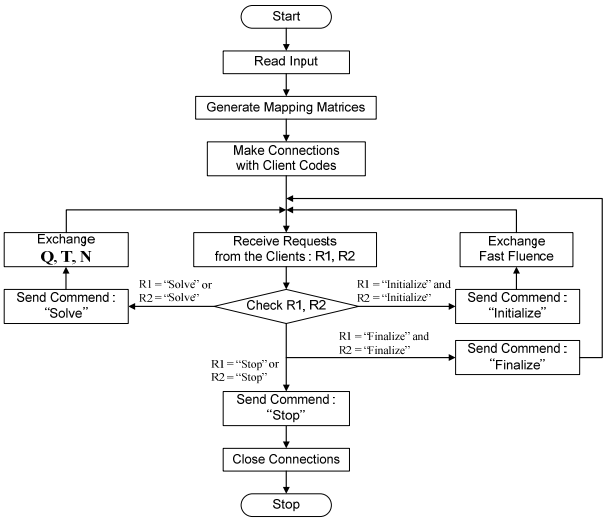


Fig. 5. Flowchart of INTCA for neutronics/thermos-fluid coupled calculation.

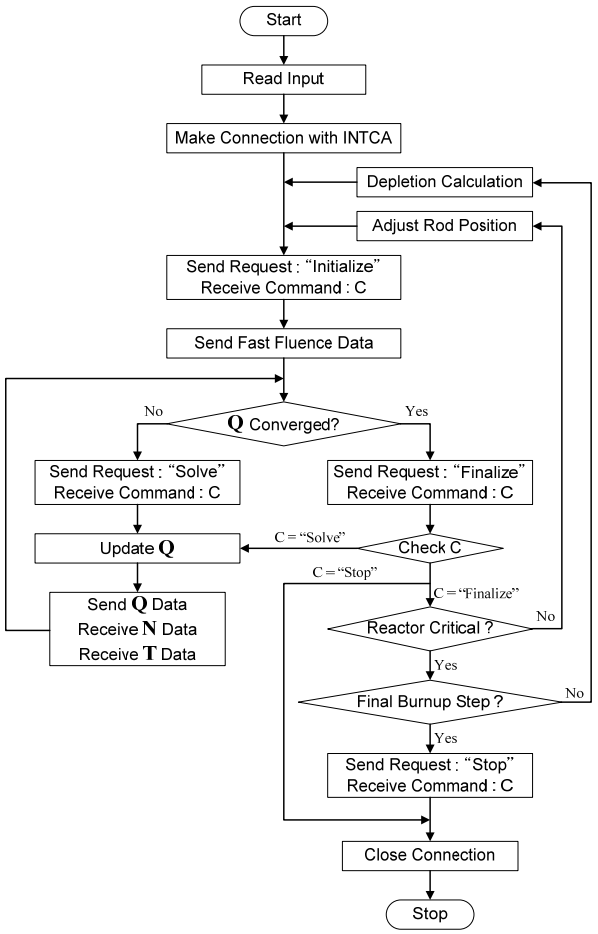


Fig. 6. Flowchart of CAPP for coupled depletion calculation with critical control rod position search.

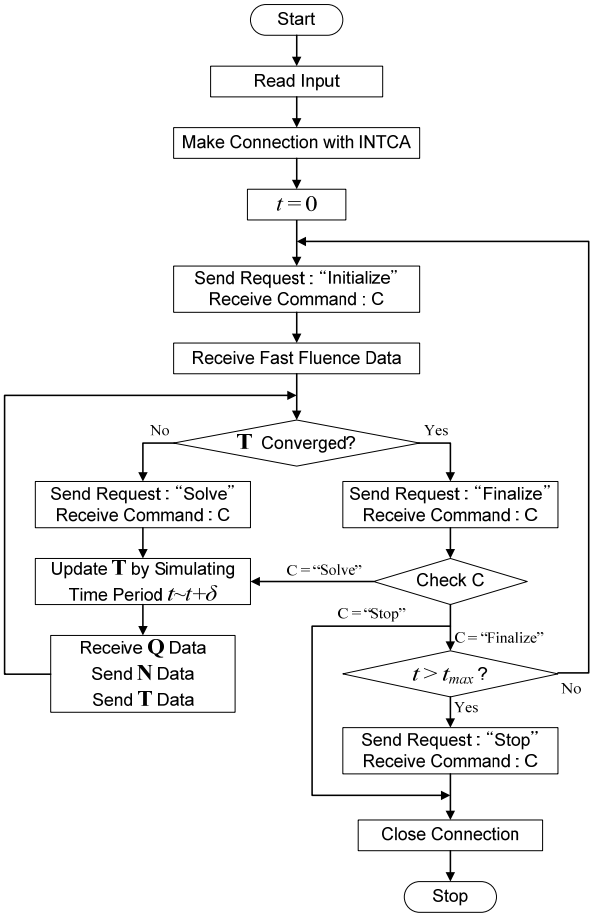
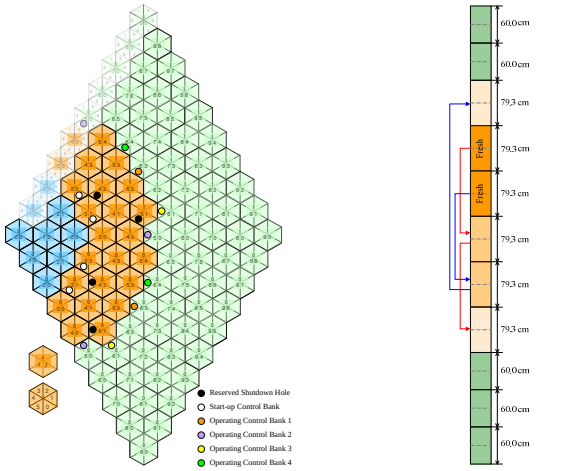


Fig. 7. Flowchart of GAMMA+ for coupled steady state calculation.

3. Numerical Results

Fig. 8 shows the CAPP nodalization for reactor core of PMR-200 [4]. One third of the core was modeled with a rotational symmetry. Fig. 9 shows the GAMMA+ nodalization for the PMR-200 core. The mapping between the cells of CAPP and those of GAMMA+ is not exact at the periphery of the side reflector. However, the importance of the periphery of the side reflector is small enough in the neutronics calculation. The coupled analysis was performed on the beginning of cycle (BOC) condition of the equilibrium cycle obtained by performing CAPP stand-alone multi-cycle depletion calculation with a core reloading scheme shown in Fig. 8(b). In the CAPP stand-alone calculation the imbedded thermo-fluid solver in the CAPP code was used to calculate the temperature for thermal feedback. During the coupled calculation, the two codes exchanged coupling data at every 15.0 sec in GAMMA+ fluid problem time, which corresponds to solid problem time of ~1500 sec because GAMMA+ uses different time scale for fluid and solid during the null transient calculation for steady state. The solution of the coupled calculation was converged in 12 couplings, which corresponds to 180.0 sec and ~18,000.0 sec in GAMMA+ fluid problem time and solid problem time.



(a) Radial configuration (b) Axial configuration

Fig. 8. Core configuration of PMR-200 for CAPP.

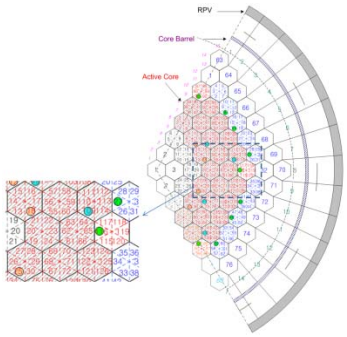


Fig. 9. PMR-200 reactor configuration for GAMMA+

Fig. 10 shows the evolution of effective multiplication factor during the coupled steady state calculation. The effective multiplication factor converged to 1.04338. Fig. 11 and Fig. 12 show the evolution of the radially-averaged axial power density and temperature profiles, respectively. Starting with the flat initial guess, power density profile converged to a slightly bottom-skewed final profile. The linear temperature induced by the flat power profile evolves gradually into a non-linear shape during the coupled calculations.

4. Conclusions

In this work, a code system for coupled neutronics and thermo-fluid simulation of VHTR was developed using CAPP and GAMMA+ codes. The coupled code system was applied to BOC steady state analysis of equilibrium cycle of PMR-200. Coupled calculation showed reasonable results. Further efforts should be made for the verification and validation of the coupled code system.

Acknowledgements

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References

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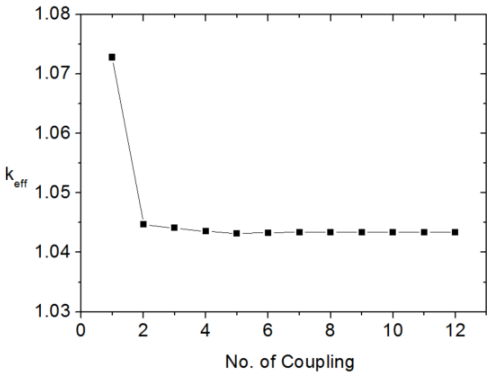

Fig 10. Evolution of effective multiplication factor.

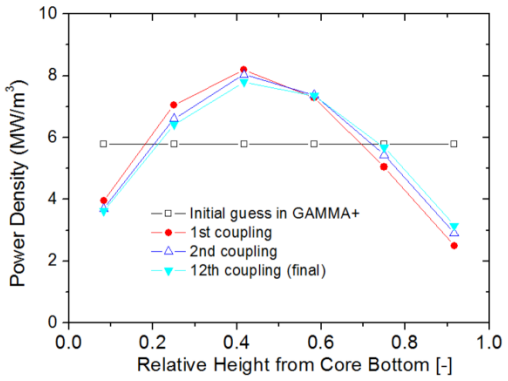

Fig. 11. Evolution of axial power density profile.

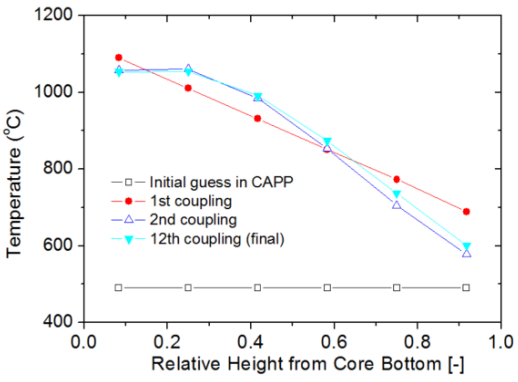

Fig. 12. Evolution of axial fuel temperature profile.